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Preliminary results on forcing vine regrowth to delay ripening to a cooler period

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Summary

The most important climate-change-related effect on wine grapes is the advance in the harvest period. The increase of temperature during the whole growing season, and consequently, the warmer conditions over ripening, lead to the production of unbalanced wines with high alcohol levels, low acidities, a modified varietal aroma and a lack of color. One of the strategies to mitigate these unpleasant effects consists on delaying the berry ripening to cooler conditions. With the aim of delaying the grape ripeness more than two months, the study of a technique consisting on forcing vine regrowth has been studied. This technique consists on cutting the green shoots off, between the second and the third node of each shoot and at different phenological stages (from state G to state K, according to the Baillod and Baggiolini system, 1993); leaves and lateral shoots of the first and second nodes are removed as well. Depending on the phenological stage of vines during the forcing treatment, the fruit ripening was shifted from one month to more than two months, *i.e.* this practice was effective to shift harvest time from the warm August to the cooler October and November. Forced vines produced smaller berries with lower pH and higher acidity and anthocyanins concentration, compared to non-forced vines. This treatment is an effective technique to restore the anthocyanin-to-sugar ratio decoupled by climate warming.

K e y w o r d s : climate warming; trimming; delayed maturation; anthocyanins; thermal decoupling.

Introduction

Global warming is an indisputable fact. One of the most important climate-change-related effects on wine grapes is the advanced harvest time. With increased temperatures and warmer ripening periods, it would be more natural to produce unbalanced wines with high alcohol levels, low acidities, a modified varietal aroma and a lack of color (Mira de Orduña 2010, Palliotti *et al*. 2014). The latter is known to be a consequence of the decoupling effect of anthocyanins and sugars accumulation in red varieties (Sadras and Moran 2012). That is, sugar accumulation in berries is accelerated while phenolic maturity is retarded due to the inhibition of some related key enzymes in the metabolic pathways of phenols biosynthesis (Mori *et al*. 2007). One of the strategies to restore the anthocyanin-to-sugar ratio, is to delay the berry ripening to cooler conditions (Palliotti *et al*. 2014, Martínez de Toda *et al*. 2013).

In this sense, several management techniques have been proposed, such as light pruning (Schultz and Weyand 2005), post-veraison apical-to-the clusters leaf removal (Palliotti *et al*. 2013), late winter pruning (Friend and Trought 2007, Zheng *et al*. 2017a), late irrigation (Freeman *et al*. 1980), application of antitranspirants (Filippetti *et al*. 2011) and shoot trimming (Filippetti *et al*. 2011, Martínez de Toda *et al*. 2014, Zheng *et al*. 2017b). Palliotti *et al.* (2014) make a classification of the different proposed techniques: a) techniques based on exploitation of carbon and nutritional competition between developing organs, b) techniques based on the induction of a temporal and calibrated source limitation, and c) techniques based on the use of growth regulators. With each of these techniques, ripening can easily be delayed between 10 and 15 d. Combining several of these techniques, maturation can be potentially delayed between 15 and 45 d. This delay is big enough to postpone harvest times to cooler weather conditions in several viticultural areas. However there are extremely warm zones such as the ones located in the V Winkler regions, with more than 2,220 °C between April and October (Winkler *et al*. 1974), where the harvest is carried out in the first days of August (for example, Montilla-Moriles and Ribera del Guadiana, Spain). In these cases, if the ripeness delay is one month and a half approximately, harvesting time would take place in the middle of September, when average daily temperatures are still quite high. Then, we would need to delay grape ripeness between two and three months, but the techniques mentioned above are not enough.

With the aim of delaying grape maturation of at least two months, it has been proposed a technique based on forcing vine regrowth (Gu *et al*. 2012). It is a bold method to fight against climate warming that could be only developed in really warm viticultural regions. It consists in shortening the growing shoots to several nodes with the aim of forcing vine re-growth; lateral shoots, leaves, and primary clusters are removed. The grapevines that grow under conventional practices and conditions, develop the initiation of the inflorescences for the following year's crop in the buds of the shoots during the current season, but they normally do not break during the current growing season because of the paradormancy. This effect is due to the inhibition produced by shoot tips, lateral shoots, and/or leaves (Lavee and May 1997). However, the buds can be forced to break up during the current season as they are not fully dormant and do not

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require chilling. In order to force budbreak, shoot regrowth, and cropping, the source of inhibition needs to be physically or chemically removed (Lin *et al*. 1985, Dry 1987, Lin 1987, Fang *et al*. 2000, Pommer 2006).

According to Gu *et al*. (2012), when performed in June forcing treatment shifted fruit ripening from the warmer to the cooler portion of the growing season, with more suitable temperatures for ripening. As expected, forced vines gave smaller berries and their juice showed a lower pH, higher acidity, and higher contents of anthocyanins, tannins, and total phenolics, compared to non-forced vines. Apparently, it is a promising technique, but there are two requirements for its application: 1) the newly formed "basal compound" buds should be fruitful; 2) the buds should be in a pre-dormancy stage. Therefore, the timing of forcing treatment is a very important factor to be considered. The formation of dormant buds usually coincides with the gran period of growth of the shoot (Keller 2015). It therefore can be argued that the forced vines can give production even in the very early phenological stages (*i.e.* 6-8 leaves separated, stage F based on Baillod and Baggiolini system 1993). Nevertheless, when the forcing treatment is carried out later, more production can be obtained (Gu *et al*. 2012). In spite of everything, the forcing technique must be performed before veraison, because dormant buds gradually lose the ability to break in 2-3 weeks along with the slowing down of shoot growth (Reynier 2002).

There are only a few works describing the use of the forcing treatment in order to improve fruit and wine quality in warmer regions (Dry 1987, Liu *et al*. 1998, Fang *et al*. 2005, Gu *et al*. 2012), but any of these have ever been developed in Spain. The general objective of the present study was to evaluate the forcing technique in Rioja appellation (Spain), as well as determining the optimal timing of application as a function of vine development and berry ripening delay. It is vital to find out an appropriate time to apply forcing technique with the purpose of delaying fruit sugar accumulation significantly, without affecting the vine yield. To our knowledge, few studies have been focused on this point and there is no general agreement. The specific objectives of this study were: (1) assess the effects of forcing at different growth stages on yield components and fruit composition; (2) determine the optimum timing of forcing and the optimal number of nodes left to obtain different yields; (3) verify whether a delayed ripening period due to forcing could improve the acidity and the anthocyanin-to-sugar ratio.

Material and Methods

Plant material: A three-year (2015 to 2017) study was conducted in the experimental vineyard of the University of La Rioja (42°27′N, 2°25′W, 370 m.a.s.l.), Logroño, North of Spain. Vines of *Vitis vinifera* L. 'Tempranillo' (clone CL-306) and 'Maturana Tinta' grafted on 110R rootstock were planted in 2010. Rows were 36 m long, north-south oriented with the spacing of 2.4 m (between rows) and 1.2 m (within row) including 30 vines each. Vines were trained to vertical shoot positioning with two arms and pruned to six spurs (12 buds) per vine. In 2015, drip irrigation was applied to all the treatments with an average amount of 4.5 L·vine·d^{-1} from the beginning of July, when about 70 % of the control shoots ceased growing, until the end of August. In 2016 and 2017, the same pattern of irrigation lasted from the middle of July till the end of August. The vineyard was managed in accordance with standard viticulture practices of Rioja appellation.

Experimental design and forcing treatments: Every year the experiments were conducted at different locations within the vineyard because our interest was not to study the long-term effects of this technique; in these first experiments we just wanted to determine the best dates of forcing. In 2015 and 2016 three adjacent rows of 'Tempranillo' were selected for the study. In 2017 three adjacent rows of 'Tempranillo' and three additional rows of 'Maturana Tinta' were considered. Vines grown under conventional practices were used as controls. The Baillod and Baggiolini system (1993) was applied to identify the growth stages of forcing treatments. The influence of different forcing dates since one month before anthesis (G-H stage) to one month after blooming at approximately 10-15-d intervals was studied. Specific dates and phenological stages for each year and treatment are presented below. In 2015 the experiment was applied on 'Tempranillo' and consisted of one control and five forcing treatments applied on 18 May (stage G-H), 25 May (stage H), 10 June (stage I-J), 23 June (stage K) and 6 July (stage L). In 2016 the experiment was also applied on 'Tempranillo' and consisted of one control and five forcing treatments applied on 17 May (stage G-H), 3 June (stage H), 15 June (stage I), 30 June (stage J) and 12 July (stage K). After two years of experiences on 'Tempranillo' we found it interesting to extend the study to other varieties and, thus, in 2017 the experiment was applied on both 'Tempranillo' and 'Maturana Tinta'. An untreated control was compared to four forcing treatments that were applied on 8 May (stage G-H), 17 May (stage H-I), 30 May (stage I) and 16 June (stage K). In 2016 and 2017 the forcing was not done in stage L because in 2015 the delay at this stage was excessive and the grape did not reach a complete maturity. In order to know the temperature conditions during the period of application of forcing, the average monthly temperatures of May, June and July provided by the observatory of Logroño were considered for the three years of study. Forcing consisted of removing, when developed, the summer lateral shoots and leaves after the growing shoots were trimmed to two nodes. Three adjacent rows were selected to form a completely randomized block design, with each row as a block. Within each row, groups of 5 adjacent vines each (sub-replicates) were randomly assigned to the different treatments so 15 vines per treatment were considered.

Vine phenology, growth and grape characteristics: The time of anthesis, veraison and harvest were recorded for each replicate. Leaf area (LA) per vine was calculated at harvest by multiplying LA per shoot by shoot number per vine. Leaf area per shoot was estimated as described in Smart and Robinson (1991). Specifically, at harvest, 15 shoots per treatment were collected randomly. All the leaves on each shoot were removed and weighed. On the other hand, 100 3.80 cm^2 discs from randomly selected leaves were weighed as well. Finally, LA per shoot was estimated by multiplying the quotient of the two weights (all the leaves and 100 discs) by 380. At harvest, per each treatment replicate, bunch number per vine was recorded to assess shoot fruitfulness, and bunch weight was measured on 10 randomly selected bunches at harvest. Two bunches per vine were randomly chosen from two different shoots corresponding to ten bunches per replicate and thirty bunches per treatment. In the case that there were two bunches in the selected shoot, the lower one was chosen. The yield per vine was determined by multiplying the number of bunches per vine by the corresponding mean weight. Average berry weight was determined on 100 randomly sampled berries from all the 5 vines of each replicate.

In 2015, grapes from all the treatments were tried to be harvested and analyzed at the same total soluble solids (TSS) level (22-23 °Brix, which is a common range for commercial grapes in the region). In the case of the last three forcing treatments, the grapes did not reach the designated ripening level so they were picked at a lower TSS on November 13 and 16. The 100-berry samples were subsequently crushed manually for the juice analysis. TSS, pH and titratable acidity (TA) were analyzed by standard methods (OIV 2014). The concentration of the total anthocyanins was measured according to Iland *et al*. (2004). Grape chemical composition was only studied in 2015 because in 2016 and 2017 the number of clusters was extremely low in the forced treatments and its composition could not be compared with that of the control. Statistical package SPSS 16.0 (SPSS Inc., Chicago, US) for Windows was used for the statistical analysis. Data were analyzed year by year. One-way analysis of variance (Anova) was performed and in the case of the existence of significant differences, the mean separation was carried out with $p < 0.05$ using Tukey's test.

Results

Effects of forcing treatments timing on phenology, growth and grape production: All forcing treatments delayed anthesis, veraison and harvest date compared to control vines, with an increasing effect when the forcing treatment was postponed (Tab. 1). Forced vines had more shoots than control vines. The numbers of forced shoots generally decreased as forcing was delayed. Especially noteworthy was the behavior of 'Maturana Tinta': for the forcing treatment carried out on 16 Jun, in Stage K, there was no sprouting of any shoot. The number of bunches in the forcing treatments was highly variable for the different years of study. Only in 2015 the number of bunches was comparable to the control while in 2016 and 2017 the number of bunches was extremely low, especially in the variety 'Maturana Tinta', and generally it increased when forcing was delayed. Bunch weight was lower in the forcing treatments than in the control, with large differences observed among the forcing treatments. Berry weight was slightly lower in the forced treatments than in the control and without significant differences in most cases. Leaf area per vine in forced treatments generally decreased as forcing was delayed; in the first two forced treatments LA was equal or higher than in the control, becoming lower than control when the forcing date was delayed. The leaf area-to-yield ratio was higher in forced vines as compared to the control and, in general, much higher than 1.5 $m^2 \cdot kg^{-1}$.

Effects of forcing treatments timing on grape composition: Grape composition was only studied in 2015 because it was the only year in which the number and size of the bunches of the forced treatments was sufficient to guarantee an acceptable yield (Tab. 1). By contrast, in 2016 and 2017, the number and size of clusters in forced treatments was excessively low and not comparable to control (Tab. 1). The forcing treatments delayed ripening and harvest between one and two months as compared to the control. The delay was greater the later the treatment of forcing was made (Tab. 2). At harvest, TSS and pH values were generally lower and TA values were higher in forced vines. With respect to anthocyanins concentration compared to the control, they were higher in the first two forced treatments and lower in the last two forced treatments.

Discussion

Effects of forcing treatments timing on phenology, growth and grape production: Trimming to two nodes plus the removal of already developed summer laterals and leaves led to force the breaking of compound buds effectively and induced the regrowth of fruitful shoots. All the forcing treatments produced the sprouting of the shoots with the exception of 'Maturana Tinta' forced in stage K, in which there was no sprouting of the shoots. This lack of sprouting in this phenological stage would be due to dormancy and would mean that the installation of such dormancy occurs earlier in 'Maturana Tinta' than in Tempranillo. According to Gu *et al*. (2012), the buds should be in the phase of predormancy and the forcing treatments should be done before veraison. Our results indicate that, in 'Maturana Tinta', the forcing must be done before the stage K. Therefore, the timing of forcing is of crucial importance since dormant buds gradually lose the ability to break in 2-3 weeks along with the slowing down of shoot growth (Reynier 2002).

Forced shoots developed normally but the number and weight of the clusters as well as the berry weight and yield were generally lower than in the control, with high variability within the different years studied. Trimming to two nodes per shoot can be applied also as a good alternative to cluster thinning to reduce yield. Therefore, these results indicate that to achieve a yield comparable to control the trimming should leave more than two nodes per shoot, for example, about three or four nodes per shoot, depending on the desired yield.

Forcing induced vine regrowth and shifted fruit ripening from a warm to a cooler period of the growing season. These results coincide with those of Gu *et al*. (2012). Forcing from stage G-H to anthesis shifted fruit ripening more than one month, from the warm August to the cooler September to October period which is better suited for producing quality grape for wine-making. Forcing after anthesis shifted fruit ripening more than two months, from the warm August to the cooler October and November period. Regarding timing

Table 1

Effects of forcing treatments timing on phenology, canopy growth and yield components. Per each "year x variety" combination, different letters within a column show significant differences between values, according to Tukey's test ($P = 0.05$). NRF: No ripe fruit

Year/Treatment	Mean monthly temperatures (°C)	Anthesis	Veraison	Harvest	Shoots per vine (n°)	Clusters per vine (n°)	Cluster weight (g)	Berry weight (g)	Shoot fruitfulness	Yield (kg·vine^{-1})	Leaf area per vine (m^2)	Leaf Area/ Yield (m^2·kg^{-1})
2015 Tempranillo												
Forced on 18 May. Stage G-H	May: 16.3	12 Jul	30 Aug	15 Oct	20.0a	15.0a	185.2b	1.32ab	0.75b	2.78b	8.03a	2.88b
Forced on 25 May. Stage H	June: 20.3	17 Jul	9 Sep	23 Oct	19.5a	10.5b	144.8c	1.19ab	0.54b	1.52c	6.22b	4.09a
Forced on 10 June. Stage I-J	July: 23.2	23 Jul	16 Sep	13 Nov	20.5a	16.5a	109.0d	0.73c	0.80b	1.80c	5.15b	2.86b
Forced on 23 June. Stage K		28 Jul	23 Sep	13 Nov	16.0bc	15.5a	103.7d	1.07bc	0.97b	1,61c	5.63b	3.49a
Forced on 6 July. Stage L		30 Aug	28 Sep	16 Nov	16,5bc	13.5b	NRF	NRF	0.82b	NRF	5.80b	NRF
Unforced control		2 Jun	2 Aug	11 Sep	12.0c	18.0a	246.2a	1.52a	1.50a	4.43a	7.45a	1.68c
2016 Tempranillo												
Forced on 17 May. Stage G-H	May: 14.8	22 Jul	23 Aug	2 Oct	24.8a	1.5d	47.0c	1.30a	0.06c	0.07c	8.03a	114,71a
Forced on 3 Jun. Stage H	June: 19.3	29 Jul	8 Sep	25 Oct	20.8a	3.5cd	79.3c	1.21a	0.16c	0.27c	6.02b	22.30b
Forced on 15 Jun. Stage I	July: 21.6	12 Aug	23 Sep	15 Nov	13.5bc	8.2bcd	127.9b	1.05ab	0.60b	1.05b	3.40c	3.24c
Forced on 30 Jun. Stage J		21 Aug	10 Oct	NRF	11.8c	6.2cd	NRF	NRF	0.52b	NRF	4.12c	NRF
Forced on 12 Jul. Stage K		23 Aug	25 Oct	NRF	13.3bc	9.8bc	NRF	NRF	0.4b	NRF	4.74bc	NRF
Unforced control		12 Jun	3 Aug	7 Sep	12.0c	17.5a	220.3a	1.37a	1.46a	3.85a	5.34b	1.39d
2017 Tempranillo												
Forced on 8 May. Stage G-H	May: 17.4	26 Jun	20 Aug	5 Oct	19.4a	5.7c	113.3b	1.14a	0.29c	0.64c	7.32a	11.43b
Forced on 17 May. Stage H-I	June: 21.3	4 Jul	30 Aug	15 Oct	20.2a	2.5c	72.2b	1.31a	0.12c	0.18c	5.70ab	31.66a
Forced on 30 May. Stage I	July: 22.1	18 Jul	9 Sep	24 Oct	20.6a	12.2b	163.2a	1.19a	0.59b	1.99b	4.45b	2.24c
Forced on 16 Jun. Stage K		2 Aug	20 Sep	10 Nov	15.2bc	20.8a	163.4a	1.15a	1.37a	3.40a	5.18b	1.52c
Unforced control		30 May	20 Jul	25 Aug	12.0c	18.0a	212.7a	1.32a	1.50a	3.83a	6.84a	1.78c
2017 Maturana Tinta												
Forced on 8 May. Stage G-H	May: 17.4	26 Jun	15 Aug	5 Oct	20.8a	5.0c	131.8b	1.28a	0.24b	0.66b	5.37a	8.13a
Forced on 17 May. Stage H-I	June: 21.3	2 Jul	30 Aug	15 Oct	17.6a	2.8c	145.2b	1.21a	0.16c	0.41b	4.66a	11.36a
Forced on 30 May. Stage I	July: 22.1	18 Jul	9 Sep	24 Oct	18.6a	9.0b	67.8c	1.13a	0.48b	0.61b	4.22a	6.92a
Forced on 16 Jun. Stage K		2 Aug	20 Sep	10 Nov	0.00	0.0	0.0	0.00	0.00	0.00	0.00	0.00
Unforced control		30 May	20 Jul	25 Aug	12.0b	18,0a	209.3a	1.30a	1.50a	3.76a	5.24a	1.39b

Table 2

Effects of forcing treatments timing on chemical composition of 'Tempranillo' grapes in 2015. Different letters within a column show significant differences between values, according to Tukey's test (P = 0.05). NRF: No ripe fruit

Year/Treatment	Berry fresh weight (g)	TSS (°Brix)	pH	TA ($g \cdot L^{-1}$)	Anthocyanins ($mg \cdot g^{-1}$)
2015 Tempranillo					
Forced on 18 May. Stage G-H	1.32ab	23.1a	3.19d	7.35c	1.67a
Forced on 25 May. Stage I	1.19ab	21.9b	3.50b	7.54c	1.63a
Forced on 10 June. Stage I-J	0.73c	19.9c	3.35c	8.62b	1.13c
Forced on 23 June. Stage K	1.07bc	19.6c	3.18d	10.35a	1.09c
Forced on 6 July. Stage L	NRF	16.2d	NRF	NRF	NRF
Unforced control	1.52a	23.0a	3.56a	4.10d	1.32b

of forcing treatments, despite no clear differences occurred in terms of bunch number, bunch weight and yield in 2015, in 2016 and 2017 a trend towards increased fertility was described when forcing was applied close to anthesis. Early forcing treatments (stages G-H and H) showed lower fertility as compared to the late applications (stages I, J and K).

In relation to the global fruitfulness of the forcing treatments in the three years, an important difference was observed between the years 2015 and 2016 that could be related to the different temperature between both years at the time of the forcing. The temperatures in that time were higher in 2015 than in 2016 and it could be the cause of greater fertility in 2015. However, the year 2017 had higher temperatures in May and June than 2015 and the fertility of the forcing treatments was lower than 2015 (Tab. 1). There does not seem to be a clear relationship between the temperature and the fertility of the forcing treatments.

It seems that the fruitfulness of the forcing treatments is more related to the phenological stage in which they are carried out than to the temperature at which they are made.

The leaf area per vine of forced vines was the same or 30 % lower than control vines. Early forcing treatments (stages G-H and H) developed more leaf area than the late ones (stages I, J and K). The results on the leaf area/yield ratio in the forcing treatments, which are much higher than 1.5 $m^2 \cdot kg^{-1}$, seem much more than enough to maintain the reserves status after a severe canopy trimming, fast plant regrowth, and very late-season ripening. According to Zheng *et al*. (2017), values as high as these in the leaf area/yield ratio indicate that vines possessed sufficient leaf area to mature their berries properly and to accumulate reserves for the next years. Lower vine vigour and yields were reported previously after forcing (Dry 1987, Fang *et aI*. 2005, Liu *et aI*. 1998). However, Gu *et al.* (2012) observed no decline in vine vigour or fruitfulness when forced vines were returned to conventional growing practices during the following growing season.

Further study should be carried out to evaluate the long-term effects of forcing on grapevines, especially on nutritional reserves of perennial parts. Also, it would be interesting to apply this technique on other varieties and other growing conditions to determine the optimum timing of forcing and the optimal number of nodes left to obtain different levels of yield.

Effects of forcing treatments timing on the chemical composition of the grape: Fruit did not ripen when vines were forced after the stage K, as reported previously (Dry 1987, Fang *et al.* 2000 and 2005, Liu *et al*. 1998). Therefore, the best time to force vines at Rioja was before the stage J-K.

The quality of red winegrapes is largely determined by their anthocyanins concentration (Winkle-Shirley 2002). It is well-known that temperatures of 15-25 °C increase the accumulation of anthocyanins, while temperatures of 25 °C or higher reduce the level of these compounds (Crippen and Morrison 1986, Spayd *et al*. 2002, Yamane *et al*. 2006, Mori *et aI*. 2007, Cohen *et al*. 2008, Tarara *et al*. 2008). Moderate temperatures also result in good fruit size, TSS contents, TA and pH, assuming the growing season is warm and long enough to ripen the fruit. The cultivar best suited to a particular region usually ripens its fruit during the cooler portion of the season (Jackson and Lombard 1993).

After forcing, the longer period of fruit ripening under cooler weather resulted in smaller berries with lower pH, higher TA, and higher contents of anthocyanins, as previously reported in other regions (Dry 1987, Fang *et al.* 2005, Liu *et aI*. 1998). The mean temperatures for August, September and October 2015, obtained from the nearest meteorological station located in Logroño, were 21.7 °C, 16.8 °C and 13.5 °C, respectively. Forced treatments always kept more acidity and lower pH, even for the same level of TSS, being the possible reason that low temperatures repressed the respiratory malate degradation (Keller 2015). The best explanation for the improvement of anthocyanins concentration might be that forced treatments created a cooler ripening condition by delaying and prolonging the ripening phase.

Forced vines produced smaller berries with lower pH, higher acidity and anthocyanins compared to non-forced vines. Forcing is a promising way to restore the anthocyanin to sugar ratio decoupled by climate warming.

Conclusions

Forcing regrowth can effectively delay all the phenological stages of 'Tempranillo' and 'Maturana Tinta' grapevines to a great extent causing the ripening to occur at temperatures considerably lower than the control. Forced treatments reduced bunch number, bunch weight and vine yield. Therefore, to achieve a yield comparable to control the trimming should leave more than two nodes per shoot, for example, about three or four nodes per shoot, depending on the desired yield. Trimming to two nodes per shoot can be applied as a good alternative to cluster thinning. Early forcing treatments (stages G-H and H) showed lower shoot fruitfulness than when postponed to the stages I, J and K in 'Tempranillo' and to the stage I in 'Maturana Tinta'. Forcing treatments can improve the anthocyanin accumulation and help to maintain a relatively high level of acidity in berries. Despite the risk of a serious decline in yield, forcing is a promising way to restore the anthocyanin to sugar ratio decoupled by climate warming. Further study should be carried out to evaluate the long-term effects of forcing on grapevines. Also, it would be interesting to apply this technique on other varieties and other growing conditions to determine the optimum timing of forcing and the optimal number of nodes left to obtain different levels of yield.

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